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FROM: Francis G. Hinnant, Col, USAF
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8455 Colesville Rd, Suite 1450
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SUBJECT: Paper approval for: Use of CAIV Techniques to Build Advanced VIIRS Approaches for NPOESS Key EDRs

Enclosed are the required ten (10) copies of the subject papers. This paper will be released at the SPIE (International Society for Optical Engineering) in July of 2002. It was written by, and will be presented by employees of Raytheon Electronic Systems.

The program office has reviewed the information in the attached papers and found it appropriate for public disclosure without change.

Point of contact on this matter is Capt. Ken Speidel, NPOESS IPO/ADA at 301-427-2084 (Ext. 208).

Attachment: Presentation—10 copies

Use of CAIV Techniques to Build Advanced VIIRS Approaches for NPOESS Key EDRs

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ABSTRACT

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Visible and Infrared Imager/Radiometer Suite (VIIRS) has responsibility for 23 Environmental Data Records (EDRs), three of them key NPOESS EDRs of highest value to operational users: Imagery, Sea Surface Temperature (SST), and Soil Moisture (primary EDR from the NPOESS conical microwave imager/sounder [CMIS]). The VIIRS design was guided by a set of government requirements priorities, which were topped by key EDR performance. Taking advantage of the MODerate resolution Imaging Spectroradiometer (MODIS) heritage, Raytheon's challenge was to optimize VIIRS system performance using Cost As Independent Variable (CAIV) analyses. The SST key EDR solution combines the traditional long-wave infrared (LWIR) split window with a second split window in the mid -wave infrared (MWIR) 3-4 μm region to offer a globally robust SST algorithm operable daytime and nighttime with a precision of 0.25K, and an overall uncertainty of 0.35K (intermediate objective) across the entire SST measurement range - capability now proven by the heritage MODIS on NASA's Terra satellite. The imagery key EDR solution permits superb multi-spectral detection and discrimination of cloud presence and type along with substantial ancillary "helper bands" such as the revolutionary 1.38 μm cirrus band now proven effective by MODIS. The soil moisture solution is a cross-sensor fusion approach that combines the finer spatial resolution of VIIRS with traditional coarse resolution microwave-derived soil moisture retrievals to achieve objectives under open and partially vegetated scenes. This paper briefly describes the VIIRS sensor design, the key EDR performance, and the CAIV design process with three specific hardware and EDR tradeoff examples. Finally, the paper concludes with a description of the key risk-reduction design processes that led to a relatively low-risk (for advanced space-borne hardware programs) developmental design which is now approaching hardware realization.

Keywords: CAIV, VIIRS, SST, sea surface temperature, soil moisture, imagery, NPOESS

I. INTRODUCTION

VIIRS development focused on the convergence of two sets of technical requirements: fine spatial resolution multi-spectral imagery with excellent modulation transfer function (MTF) (e.g., for cloud and land feature discrimination) and high-fidelity spectroradiometry with superb calibration and signal to noise ratio (SNR) (e.g., for sea surface temperature [SST] and ocean color). VIIRS will replace two currently operating sensors and provide data continuity for a third: 1) the Defense Meteorological Satellite Program (DMSP) Operational Line-scan System (OLS), 2) the NOAA Polar-orbiting Operational Environmental Satellite (POES) Advanced Very High Resolution Radiometer (AVHRR), and 3) the NASA Earth Observing System (EOS Terra and Aqua) MODerate-resolution Imaging Spectroradiometer (MODIS).

The NPOESS Integrated Program Office (IPO) specified geophysical measurements [1] called "Environmental Data Records" (EDRs), rather than sensor hardware specifications. Raytheon was required to derive optimal system specifications and hardware designs from the EDRs. The development was challenging due to the desire for excellent EDR performance at affordable cost, and low risk for launch on the NPOESS Preparatory Project (NPP) flight in 2006.

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VIIRS will perform very well for three basic reasons. First, the sensor is designed specifically for the mission based on the NPOESS VIIRS government integrated requirements priority list [3], with crisp optics, low scattered light, excellent radiometry based on a proven and extensive on-board calibration system, and a comprehensive set of narrow spectral bands. Second, the algorithms leverage the combined best experience of operations and research, including MODIS, Sea-viewing Wide Field Sensor (SeaWiFS), DMSP OLS and Special Sensor Microwave Imager (SSM/I), and AVHRR theoretical basis heritage. Third, the sensor and algorithms were designed as a system [4].

1.1 VIIRS Sensor Attributes

Multiple DoD and Civil operational requirements [2] mutually supported each another through this integrated single-sensor approach that balances imaging and spectroradiometry. A welcome consequence of the driving Imagery MTF requirements and pixel aggregation is a diffraction-limited VIIRS optical design [3] with excellent track and scan MTFs. The design begins with an afocal three-mirror anastigmat (TMA) rotating telescope. The rotating TMA's collimated output is directed to a half-angle mirror (HAM), proven on SeaWiFS, toward a fixed four-mirror anastigmat (FMA) imager. This balanced optical design yields excellent image quality across the focal plane.

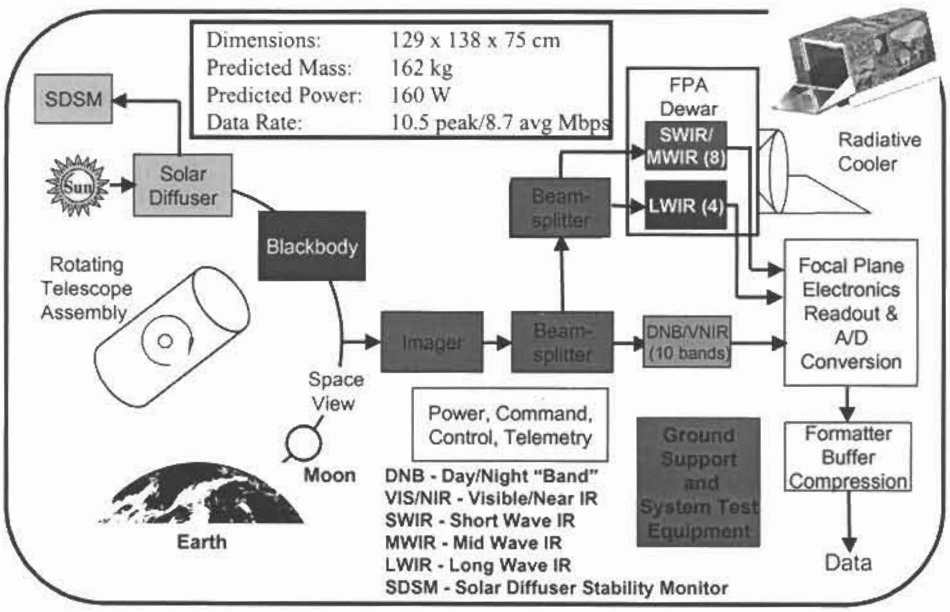

Figure 1. The VIIRS telescope rotates to view deep space, the moon, Earth, solar diffuser, and black body.

1.2 VIIRS System Introduction

The VIIRS design required iterative cost as independent variable (CAIV) trade studies discussed in section 3 below. These achieved a balanced design as illustrated in Figure 2, providing excellent spatial resolution for imagery and excellent spectroradiometry for civil operational and scientific users. The "trick" was to ensure that spatial resolution did not compromise spectroradiometry nor that spectroradiometry did not compromise spatial resolution while combining both in one sensor for lowest cost. Raytheon succeeded in finding ways [3] to employ excellent spatial resolution to enhance EDRs depending on spectroradiometry while also using excellent spectroradiometry to enhance EDRs depending on spatial resolution, as emphasized in Figure 2. The key to the design approach used to accomplish this is summarized in a patent [5]. As described in [3], VIIRS employed a special detector focal plane design similar to the concept described in [5] to achieve near-constant (2:1 vs. 6:1 edge of swath vs. nadir resolution) cross-track spatial resolution. This allowed VIIRS to offer better nadir spatial resolution, and about four times better edge of swath spatial resolution, than MODIS while also achieving substantially better nadir signal-to-noise ratio (SNR) than MODIS. As this is accomplished with the same optical aperture as MODIS allows the use of MODIS ground support equipment (GSE) to minimize VIIRS GSE cost and risk.

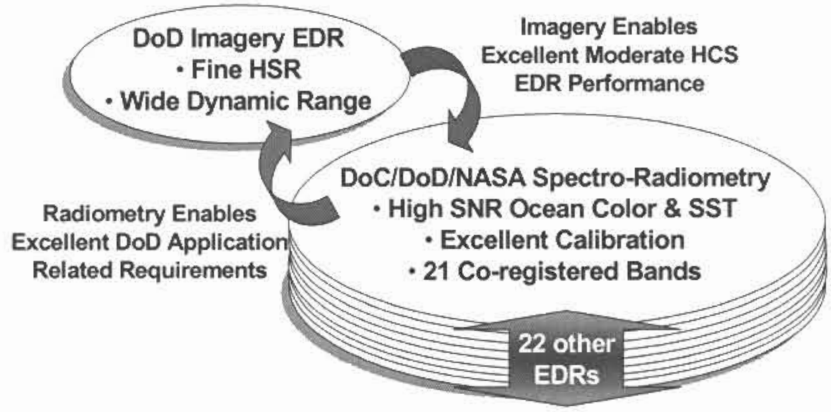

Fig. 2. The fusion of operational DoD and DoC requirements led to beneficial synergies across VIIRS.

Table 1 lists and defines the resultant 22 VIIRS spectral bands. Six visible and NIR bands carry a superscript "D" to denote their dual-gain capability first demonstrated by SeaWiFS. The high-gain states increases their signal to noise ratios over clear oceans for improved ocean bio-optical remote sensing. The 4050 nm band also has a second, high-radiance state for fire characterization. The advanced spectroradiometric capabilities of VIIRS will enable a new generation of EDR retrieval, as well as the "operationalization" of emerging retrieval techniques.

Table 1. Spectral and spatial attributes of the 22 VIIRS bands.

λ_c (nm)	$\Delta\lambda$ (nm)	Spectral Range (^{D} :dual gain)	Flight Heritage Band	GIFOV (Nadir, Edge of swath)
412	20	VIS^D	MODIS 8	0.75 km, 1.6 km
445	18	VIS^D	MODIS 9	0.75 km, 1.6 km
488	20	VIS^D	MODIS 10	0.75 km, 1.6 km
555	20	VIS^D	MODIS12	0.75 km, 1.6 km
672	20	VIS^D	MODIS 13/14	0.75 km, 1.6 km
746	15	NIR	MODIS 15	0.75 km, 1.6 km
865	39	NIR^D	MODIS 2/16	0.75 km, 1.6 km
1240	20	SWIR	MODIS 5	0.75 km, 1.6 km
1378	15	SWIR	MODIS 26	0.75 km, 1.6 km
1610	60	SWIR	MODIS 6	0.75 km, 1.6 km
2250	50	SWIR	MODIS 7	0.75 km, 1.6 km
3700	180	MWIR	MODIS 20	0.75 km, 1.6 km
4050	155	$MWIR^D$	MODIS 21/22/23	0.75 km, 1.6 km
8550	300	LWIR	MODIS 29	0.75 km, 1.6 km
10763	1000	LWIR	MODIS 31	0.75 km, 1.6 km
12013	950	LWIR	MODIS 32	0.75 km, 1.6 km
700	400	PAN	OLS L	0.75 km, 0.75 km
640	80	VIS	MODIS 1	0.375 km, 0.8 km
865	39	NIR	MODIS 2	0.375 km, 0.8 km
1610	60	SWIR	AVHRR/3A	0.375 km, 0.8 km
3740	380	MWIR	AVHRR/3B	0.375 km, 0.8 km
11450	1900	LWIR	OLS T	0.375 km, 0.8 km

II. VIIRS KEY EDR PERFORMANCE

Flying in three orbits, with contiguous global coverage every four hours, VIIRS will permit greatly improved operational products with AVHRR and OLS heritage, as well as the demonstration and deployment of a new generation of advanced data products with MODIS, SeaWiFS, and Enhanced Thematic Mapper (ETM+) heritage.

2.1 Skin and Bulk Sea Surface Temperature (SST)

From the beginning of the VIIRS design effort, SST was designated by the NPOESS Integrated Program Office (IPO) as one of six key EDRs, and a "Category 1A" (top priority) VIIRS EDR. Key EDRs were not only allowed, but expected to shape the VIIRS design. Accordingly, the VIIRS sensor's spatial, spectral, and radiometric performance was explicitly optimized for imagery and SST [4].

SST was required at 1 km nadir resolution (0.25 km objective), and 1.3 km worst-case across the 1,700 km measurement swath. There is an inverse relationship between horizontal resolution and radiometric precision. Raytheon developed the 0.75 km nadir resolution (aggregating detectors 3:1 in track near nadir, 2:1 in-track aggregation out to a 2,000 swath, and 1:1 out to 3,000 km) to simultaneously optimize spatial resolution and noise performance.

The SST solution combines the traditional long-wave infrared (LWIR) split window with a second split window in the middle infrared (MWIR) for a globally robust SST algorithm. The MWIR split window has a higher transmissivity than the traditional LWIR split window for improved atmospheric correction. The low-noise design (Fig. 2) is operable day and night with 0.25K precision, and 0.35K total measurement uncertainty (rms error) [5], and this performance has recently been demonstrated by MODIS.

Before MODIS demonstrated it on orbit, Raytheon verified by theoretical computer simulation that the 0.35 K uncertainty could be achieved using both 17-level NCEP global gridded data with multiple orbits providing daytime and nighttime observations, and a 305-profile all-season, global profile data set with very challenging vertical temperature and moisture structure. MODIS skin SST observations are validating the low-noise MWIR window observations, especially for moist tropical retrievals.

Table 2. Specified and predicted noise equivalent delta temperature

λ_c (nm)	AVHRR Spec (Entire Swath)	MODIS Spec (Entire Swath)	ATSR Spec (900 km)	VIIRS Spec/ Pred (Nadir)	VIIRS Spec/ Pred (2,000km)
3700	0.12	0.05	0.02	0.08/0.04	0.11/0.06
4050	N/A	0.07	N/A	0.06/0.02	0.09/0.03
10763	0.12	0.05	0.03	0.04/0.02	0.06/0.03
12013	0.12	0.05	0.02	0.04/0.03	0.06/0.04

2.2 Imagery and Cloud Detection/Typing

Until VIIRS is launched, operational cloud analysts and scientists will continue to be restricted to either a pair of high-resolution bands (DMSP/OLS) or five (POES/AVHRR/3) moderate-resolution spectral bands. The imagery solution provided on VIIRS includes six high-resolution bands and an additional 16 moderate-resolution bands. One of these, a reflective panchromatic band, is operable in low-light conditions down to a quarter moon. Like the OLS, and unlike AVHRR, SeaWiFS, and MODIS, growth of the field of view from nadir to the edge of the 3,000 km swath (EOS) is held to a factor of two in the along-scan direction. Uncontrolled, due to a combination of slant-path range and Earth curvature, previous sensors had growths in a 1 km nadir observation to ~6 km at EOS.

The 640, 3740, and 11450 nm bands, along with the day-night pan band fully achieve the SRD imagery requirements for manually-generated cloud detection and typing. Synergistic addition of the 865 and 1610 nm imagery bands and 16 other high signal-to-noise, moderate spatial resolution spectral bands, satisfies many objective-level requirements. These ancillary "helper bands," such as the 1378 nm cirrus detection band, provide a significant amount of new analysis information that transfers MODIS technology [6] into the operational environment as illustrated in Figure 3. It will be important to train the users so that the full multispectral value of VIIRS is realized.

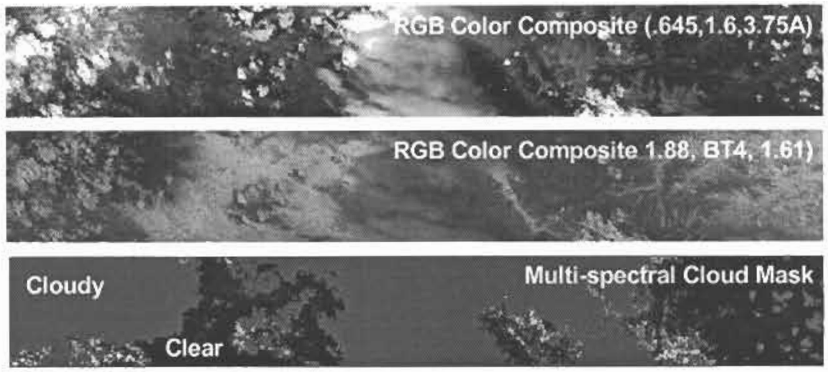

Fig. 3. All 22 VIIRS bands can be used together to produce a greatly improved cloud and sea-ice operational detection and characterization capability.

2.3 Soil Moisture

Unlike SST and Imagery, Soil Moisture (a key NPOESS EDR), was assigned a low priority for VIIRS. Under the design guidelines, this EDR was not allowed to drive the VIIRS design. Because a robust theoretical basis and practical heritage of passive microwave-based soil moisture retrievals exists, we implemented a VIIRS-Conical Microwave Imager/Sounder (CMIS) fusion solution. The approach combines the fine spatial resolution of VIIRS with traditional coarser-resolution microwave-derived soil moisture retrievals to achieve excellent results over both open and partially vegetated scenes. The estimation procedure [7] involves two steps: (1) CMIS estimates soil moisture at coarse spatial resolution. This involves inversion of dual-polarized microwave brightness temperatures. (2) CMIS-derived low-resolution soil moisture is linked to the scene optical parameters, such as Normalized Difference Vegetation Index (NDVI), surface albedo, and Land Surface Temperature (LST). The linkage of the microwave-derived soil moisture to NDVI, surface albedo and LST is based on the "Universal Triangle" approach of relating land surface parameters. The three high-resolution optical parameters are aggregated to microwave resolution for the purpose of building the linkage model. The linkage model, in conjunction with high-resolution NDVI, surface albedo, and LST, is then used to disaggregate microwave soil moisture into high-resolution soil moisture. We applied the technique to data from the Special Sensor Microwave Imager (SSM/I) and AVHRR acquired during the Southern Great Plains (SGP-97) experiment as illustrated in Figure 4. Predicted soil moisture results at higher resolution agree with lower-resolution results in magnitude and trend, and the predicted soil moisture agrees well with *in situ* measurements. Soil moisture error budget analysis gives rms error less than 5% for a typical bare field.

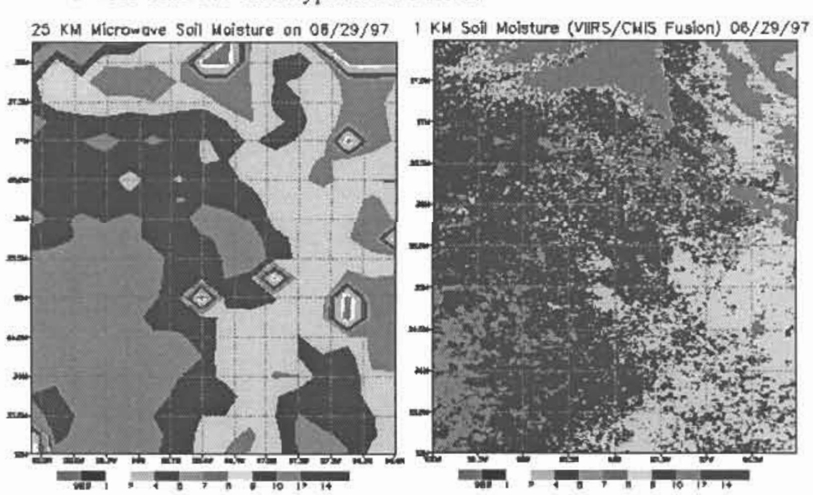

Fig. 4. Comparison of microwave-only (left panel) and microwave-electro-optical sensor fusion (right panel) approaches to soil moisture EDR retrieval validated using SSM/I and AVHRR.

III. COST AS INDEPENDENT VARIABLE (CAIV) TRADES

Cost as an Independent Variable (CAIV) tradeoff techniques were central to the VIIRS design process. The basic idea behind CAIV, and specifically for VIIRS, is outlined in Figure 5. CAIV is a process of balancing cost, performance (mission capability), and risk. The "Best Value" design is the goal of the CAIV design process. Many parameters needed to be considered during the VIIRS design effort leading to the preliminary design review (PDR). Among them were sensor architecture (multiple vs. single sensor suite), spectral band selection (number and type), and radiometric calibration accuracy, all balanced against cost and risk.

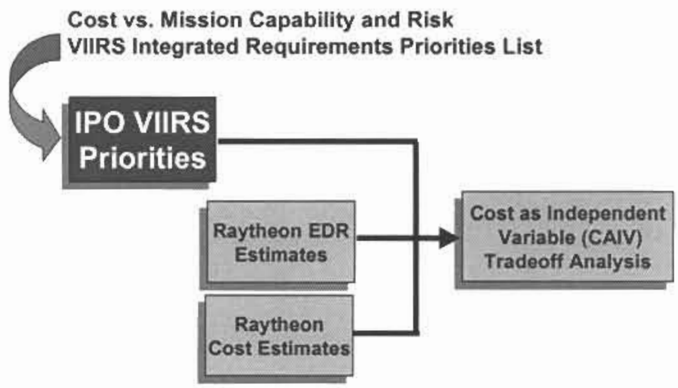

Figure 5. Cost as Independent Variable (CAIV) Optimization is driven by IPO priorities, contract, and design.

Figure 6 illustrates the sensor architecture CAIV trade leading to the selected single sensor design. The most fundamental sensor tradeoff is the scan approach, either pushbroom or cross-track ("whiskbroom") scan. Cooled shortwave infrared (SWIR) to LWIR spectral capability requires cross-track scanning to accommodate the 3000-km (112-degree) cross-track VIIRS swath with reasonable detector focal plane array (FPA) cooling requirements. A separate pushbroom or whiskbroom ocean color radiometer and Day/Night Band (DNB) imager could have been selected (as their FPAs operate near ambient temperature), but integral ocean color and DNB proved to offer Best-Value. Integral ocean color spectral bands coregistered to the SWIR through LWIR bands provide significant benefits to Aerosol, Cloud, and Land EDR performance [4]. This enables good ocean color performance in all orbits under favorable sun-angle conditions (typically less than 70 degrees solar zenith angle where sun-glint is absent). Ocean color operation in both morning and afternoon nominal orbits with a nadir-pointing sensor enables SRD-specified ocean color refresh in spite of sun-glint. Finally, integral ocean color is substantially less costly than a separate sensor.

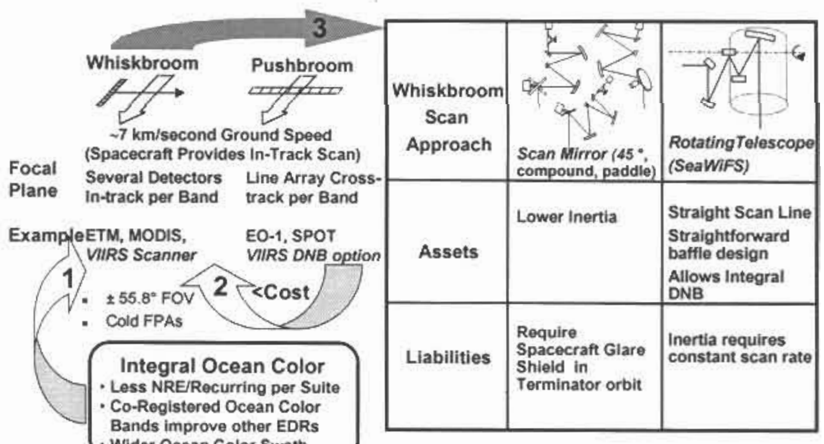

Figure 6. Key Tradeoffs leading to Best Value single sensor VIIRS design.

Figure 7 illustrates the spectral band selection CAIV trade. VIIRS spectral capability was optimized based on the IPO's priorities listed in Table 1. As illustrated in Figure 7, this capability is dramatically better than existing operational sensors, yet also represents a 40% simplification relative to MODIS. At the same time, however, these 22 bands comprise comparable spectroradiometry to MODIS in the context of the VIIRS EDRs, because the reduction in spectral coverage primarily affects the MODIS sounding channels. Moreover, five of the 22 bands provide fine-resolution capability to address Imagery, the Normalized Difference Vegetation Index (NDVI), and Snow Cover EDRs. Therefore, VIIRS offers both MODIS-comparable spectro-radiometry and improved imaging capability compared to OLS, while the integrated single-sensor design allows coregistration of all bands, benefiting all the EDRs.

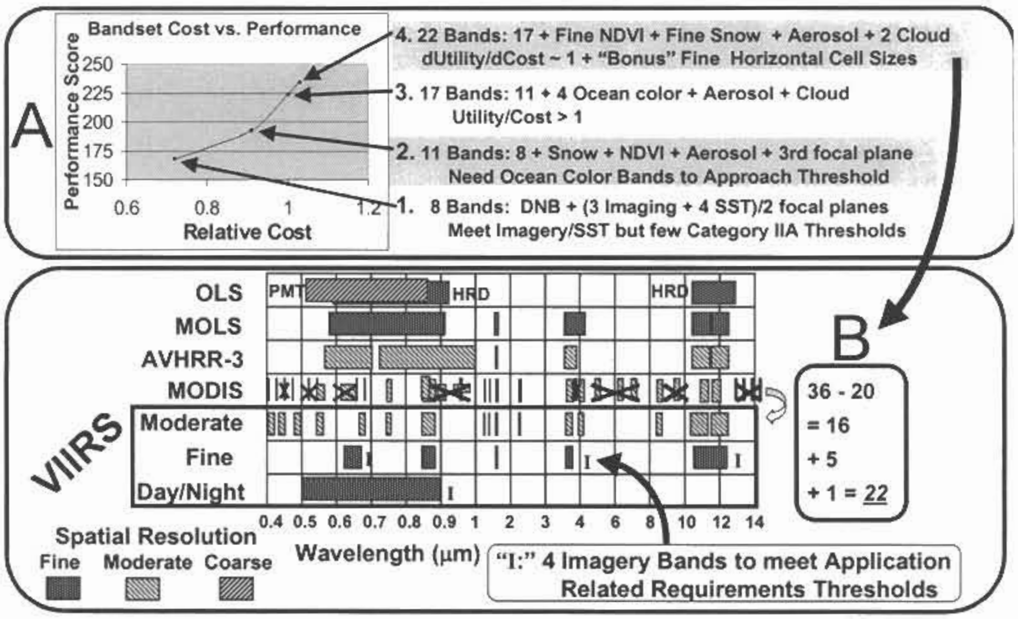

Fig. 7. Cost as an independent variable (CAIV) drove spectral band selection

Figure 8 illustrates the reflective spectral bands radiometric accuracy CAIV tradeoff driven by the aerosol optical thickness (AOT) EDR. The VIIRS SRD requirements on AOT are listed in the top center box. To meet these requirements, as indicated in the graphic, better than 2% radiometric accuracy would be required. This is not only difficult, it has not yet been achieved by a remote sensing instrument, with the best accuracy so far being achieved by MODIS at about 2%. Therefore, we considered the performance degradation to AOT of specifying a realizable 2% accuracy requirement on VIIRS. The bottom line is shown in the bottom right box in the figure. 99% of aerosols found globally and temporally have AOT less than 0.5, for which it is possible to achieve an AOT accuracy of 0.02 or better with a sensor offering <2% radiometric accuracy. Above 0.5, the AOT accuracy will degrade, so that Raytheon selected a ramp function accuracy for AOT > 0.5. This does not meet the AOT threshold established by the government during the contract competitive phase. The government requirements priorities included AOT among the higher priority EDRs, for which "compelling benefit" to the government had to be demonstrated if a contractor chose to take exception to the threshold requirement. Raytheon took the risk of specifying worse than AOT threshold performance in the company's VIIRS proposal on the basis of the CAIV trade of Figure 8 - a risk that could have cost Raytheon the program if the government did not agree with the CAIV trade.

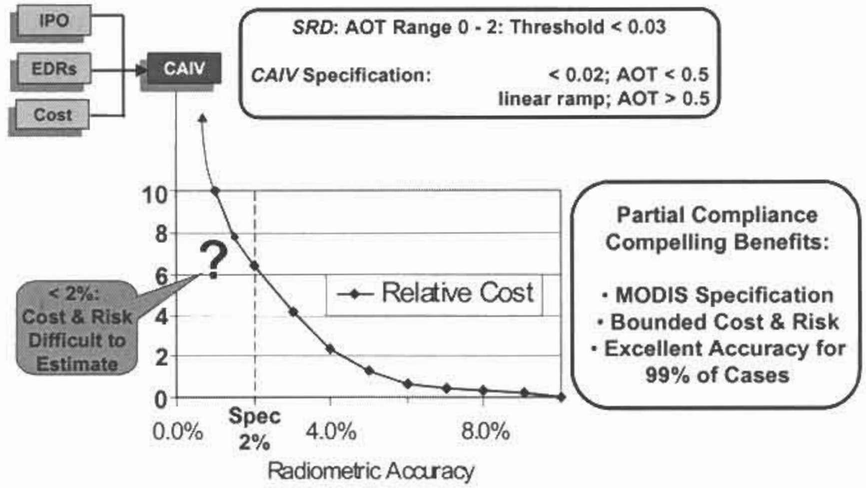

Fig. 8. Aerosol EDR performance vs. sensor absolute radiometric accuracy CAIV Trade

IV. VIIRS Heritage Reduced Risk

VIIRS is designed to take advantage of heritage to lower risk. Several features are particularly important.

4.1 Embracing Flight Heritage and Lessons Learned

Recent flight experience demonstrated many VIIRS technologies as indicated in Figure 9. SeaWiFS proved the rotating telescope. The Mars Thermal Emission Imaging System (THEMIS) demonstrated "butcher-block" spectral filter assemblies and precision diamond-turned bolt-together optics needed to affordably achieve superb VIIRS MTFs. MODIS proved the on-board calibrators and spectral band selections, as well as many advanced multispectral algorithms. MODIS correction of optical ghosting, electronic cross-talk, out-of-field response, rotating mirror reflectance versus scan angle, and other remote sensing subtleties further lowered VIIRS design risk. Leveraging flight proven technologies improved performance dramatically over AVHRR and OLS while lowering risk.

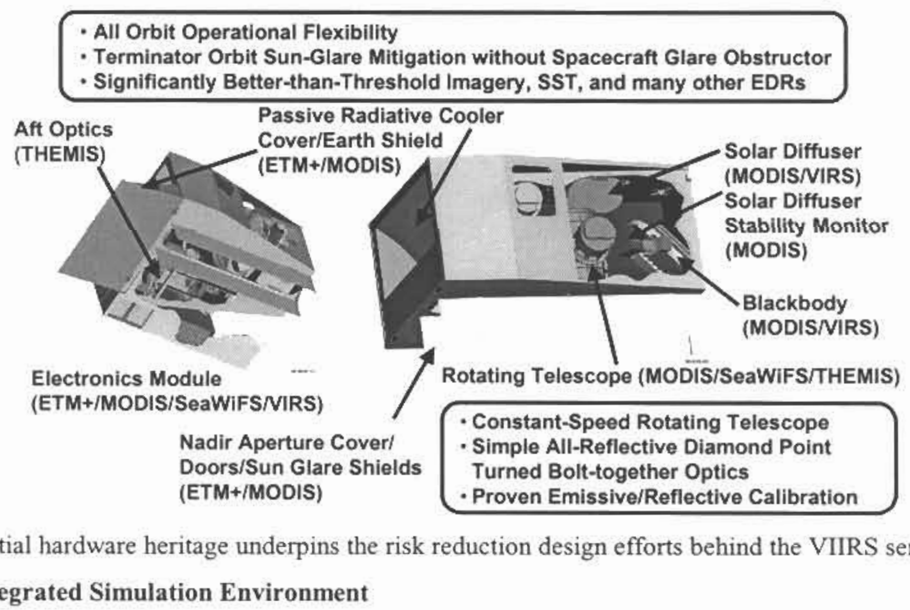

Figure 9. Substantial hardware heritage underpins the risk reduction design efforts behind the VIIRS sensor.

4.2 Flexible, Integrated Simulation Environment

Because of the design paradigm—build an optimized system with cost as an independent variable to meet prioritized data product requirements—an end-to-end system level simulaion testbed illustrated in Figure 10 was essential. Use of the test bed as the centerpiece of the systems engineering process enabled iterative design optimization and validation. The end-to-end simulation test bed illustrated in Figure 10 permitted optimization of data and sensor specifications as well as geophysical retrieval algorithm and sensor designs. As indicated on the top left of Figure 10, ground truth test data sets are converted into simulated Top-Of-Atmosphere (TOA) radiances. These serve as inputs to a sensor simulation, which produces digital data representative of those anticipated from the sensor. These digital data are converted to EDR estimates using the EDR retrieval algorithms that would be used on real sensor data. Finally, the retrieved EDRs are compared to ground truth as illustrated in the center of Figure 10. Iterative changes to the sensor specification and EDR algorithms as well as to the EDR requirements allow system CAIV trade optimization.

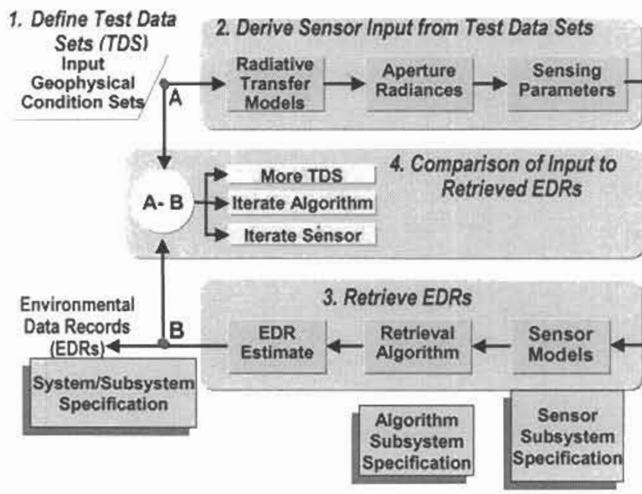

Figure 10. End-to-end test bed tool for specification derivation & verification

4.3 Industry, Government, and University Interaction

The Raytheon VIIRS effort built on a partnership among industry, government, and academia with talented individuals from multiple disciplines. Government participants encouraged design process innovation and maintained continuous oversight. Academia provided singularly qualified science experts in niche remote sensing areas. As illustrated in Figure 11, the integrated team effort included a careful evaluation of the testbed validity. This evaluation demonstrated that the testbed results applied to known flight systems MODIS, SeaWiFS, and TRMM VIRS (all built by Raytheon SBRS) were consistent with the actual flight data and data products derived from those systems.

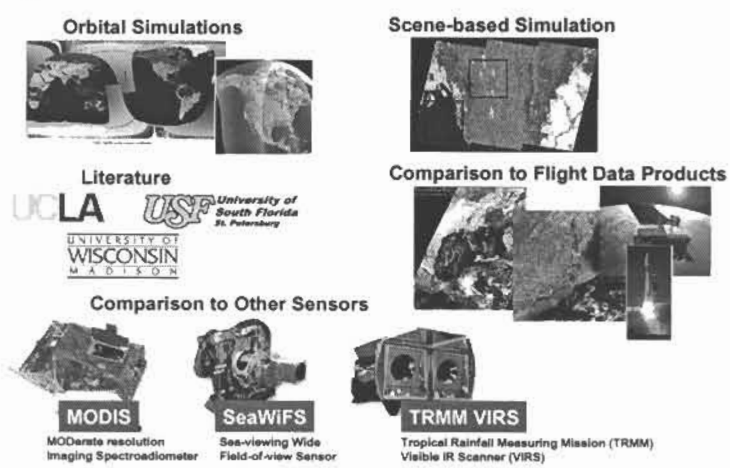

Figure 11. Simulations and design activities encompassing university simulation and algorithm efforts were double-checked against Raytheon flight hardware data products to prove the validity of the VIIRS testbed.

ACKNOWLEDGMENTS

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